Statistical Properties of the Acoustic Field in Inhomogeneous Oceanic Environments

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LONG-TERM GOALS

- To develop an effective method of description of statistical properties of acoustical signals and calculation of false alarm rate for a given probability distribution of locations of acoustic source(s) in space.
- To quantify the degree to which uncertainty in the knowledge of cross-range variation of environmental parameters and their variation in time (or purely statistical information on the variations) degrades the ability to detect, locate, and track targets acoustically.

OBJECTIVES

1. To develop an effective numerical algorithm of calculation of second statistical moments of the acoustic signals measured by a set of receivers located on sea bottom or arbitrarily distributed in space for inhomogeneous ocean waveguide (including the case of uneven bottom) in terms of probability distributions of source location.

2. To investigate probability distributions of acoustical signals for typical environments including both deep water and littoral cases.

3. To develop an efficient formalism of transferring uncertainty in the 4-D spatial-temporal fields of environmental parameters into uncertainties of observable acoustic quantities.

4. To quantify the amount of environmental information necessary to achieve a specified accuracy of acoustic field modeling and to determine, for various nearshore hydrodynamic processes of interest, when 2-D (as opposed to 3-D and 4-D) environmental and propagation models are acceptable.

5. To develop a numerical algorithm for predicting statistical moments of acoustic signals in underwater waveguides with horizontally-inhomogeneous and time-dependent parameters.

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APPROACH

In modeling effects on the acoustic field of (i) cross-range environmental gradients and (ii) time-dependence of the sound speed and the problem geometry, our approach is based on considering these effects as perturbations with respect to sound propagation in a range-dependent, stationary waveguide. The problem is solved analytically for the three leading terms of the perturbation series. Account of the second-order terms is crucial because it is these terms that are responsible for ray travel time and mode phase biases. The perturbation solution will be used to determine statistical properties of various acoustic observable quantities in terms of respective statistical properties of environmental parameters. The task of relating statistical properties of the sound field to statistical properties of the environment is greatly facilitated by the fact that the perturbation theory gives variations in travel times and other acoustic quantities as integrals in the source/receiver vertical plane of certain functions of cross-range gradients and time derivatives of environmental parameters. Kernels of the integrals are determined by the acoustic field in an unperturbed, stationary, range-dependent environment and are independent of the cross-range environmental gradients and time derivatives.

Another way to quantify uncertainties in the acoustic field and associated probabilities of the detection and false alarm rate relies on using scattering matrix for acoustic modes. Scattering matrix (SM) describes the process of transformation of modes when propagating through inhomogeneous region. SM depends on the parameters of the inhomogeneities but does not depend on coordinates of the source and receivers. Thus the dependencies on the environmental parameters and positions of the source and receivers are factored out and can be studied separately. In particular, if the SM is exactly known and position of the source is unknown, uncertainties of the detection can be expressed in terms of convolution of the SM with assumed probability distribution of the source location. On the other hand, if SM is not exactly known, additional uncertainty in source detection can be expressed in terms of statistical moments of SM itself.

WORK COMPLETED

Conditions have been determined under which acoustic fields in the ocean with currents can be modeled as fields in a motionless medium with flow velocity-dependent effective sound speed and density, regardless of a particular representation of the field assumed in the model (Godin, 2001a).

“False” Doppler shifts resulting from medium nonstationarity rather than source-receiver motion have been calculated theoretically for ray and modal arrivals. Magnitude of the “false” Doppler shifts increases with propagation range, can reach a few meters per second in the equivalent source-receiver radial velocity, and is sensitive to path-averaged intensity and correlation length of the internal wave field (Godin, 2001b).

The expression for RMS error of the acoustic field assuming uniform probability distribution of the source position with respect to depth in terms of the SM was obtained. The model of the medium, which will be used for numerical evaluation of the SM in the case of uneven bottom, was developed. This model will use piecewise linear continuous approximation of the sound speed and density field. The equations governing statistical moments of the acoustic field due to scattering at internal waves were obtained.

RESULTS

The perturbation theory has been shown to apply to most propagation scenarios of practical interest, both in deep and shallow water, and has been utilized to quantify effects of the horizontal refraction due to deterministic horizontal inhomogeneities. For instance, under conditions of the 1993 Pacific Shelf sea trial (Chapman et al., 1996) where CW tones in the band f = 45 –72 Hz propagated in the water of depth 300-500 m over bottom with slope of 6-8 degrees, corrections to mode phase due to horizontal refraction were found to exceed 2π at distances of 7 km. Being approximately proportional to the fourth power of the grazing angle, the corrections proved strongly dependent on the mode order, thus leading to significant variations in the transmission loss compared to predictions obtained within the uncoupled azimuth approximation. As another example, Figs.1 and 2 show adiabatic mode phase errors resulting from the uncoupled azimuth approximation and the perturbation theory, compared to an exact solution for a wedge-shaped waveguide with pressure-release boundaries and wedge angle 3.81 degree. The waveguide is occupied by a homogeneous fluid with sound speed 1500 m/s; water depth at the source location is 400 m. Note large phase errors within the uncoupled azimuth approximation. Because curvature of mode trajectories in the horizontal plane is taken into account by the perturbation theory, it always provides an improvement over the uncoupled azimuth approximation. Depending on mode order and frequency, improvement in the accuracy of phase modeling easily reaches two orders of magnitude (Fig. 2).

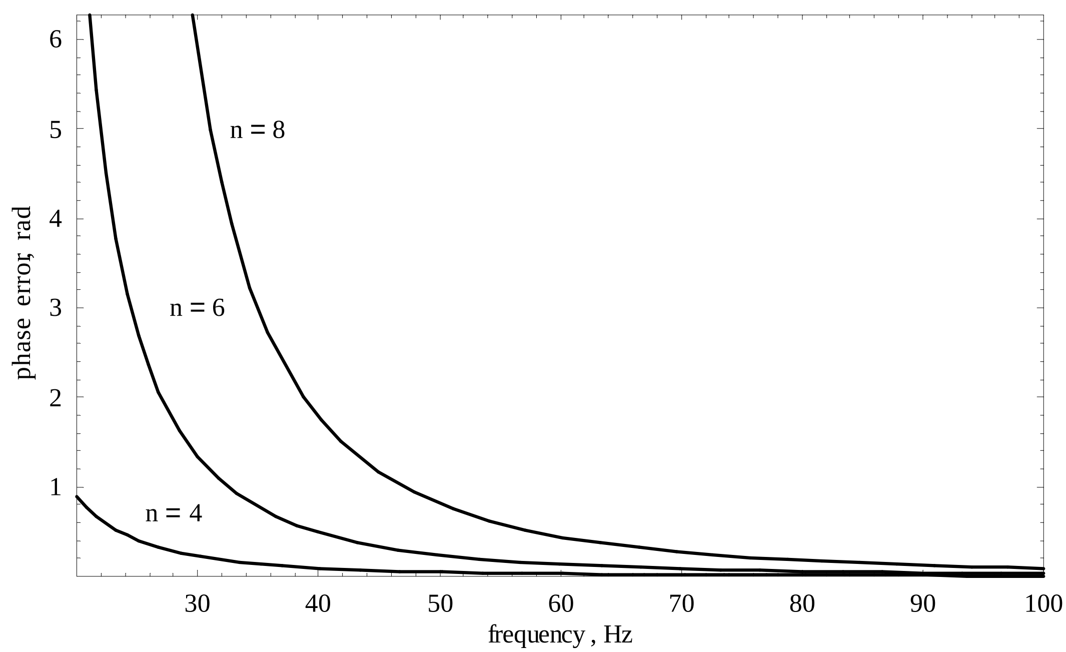

Figure 1. Deviation of adiabatic mode phase (in radians) calculated within the uncoupled-azimuth approximation from its exact value at cross-slope propagation at a distance of r = 7 km from the source.
[Graph: The phase error for the fourth mode exceeds $\pi/4$ at f = 20 Hz, for the sixth mode it exceeds 2π at f = 20 Hz, and for the eighth mode it exceeds 2π at f = 30 Hz. For all modes the errors rapidly and monotonously decrease with frequency and mode order.]

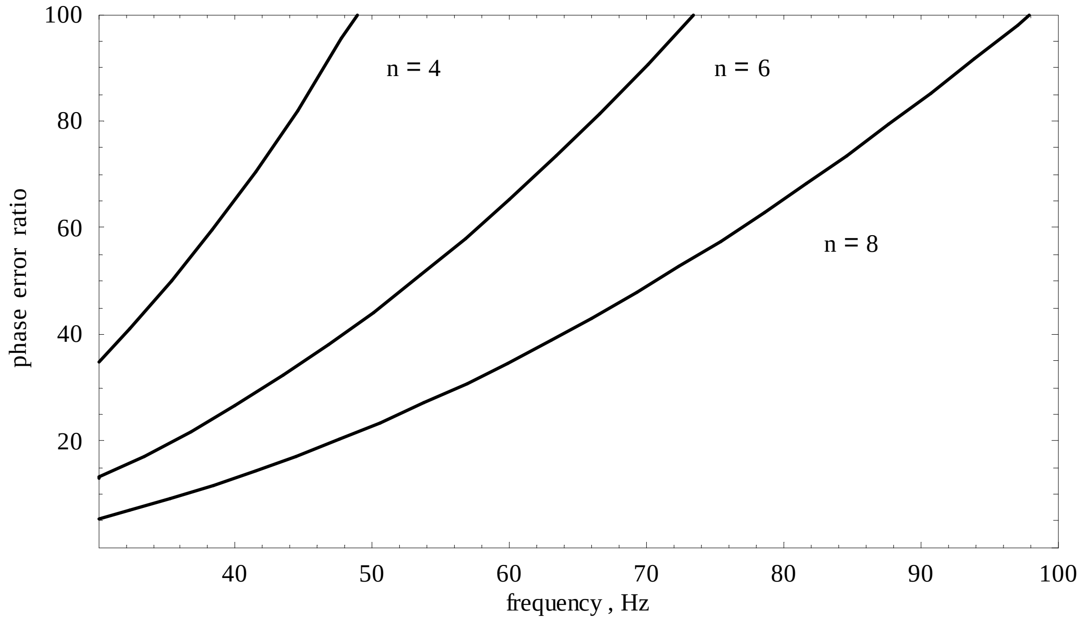

Figure 2. Ratio of the phase errors due to the uncoupled-azimuth approximation to errors of the perturbation theory.
[Graph: At f =30 Hz, the ratio is, approximately, 35, 8, and 5 for modes n= 4, 6, and 8, respectively. It exceeds 100 for f > 49 Hz (n =4), f > 74 Hz (n =6), and f > 99 Hz (n =8). For all modes the ratio monotonously increases with frequency and decreases with mode order.]

IMPACT/APPLICATIONS

The most immediate impact of this work will be on the use of deterministic models of underwater sound propagation for making tactical decisions. Results of this work will quantify, in a statistical sense, reliability of predictions for various acoustic observables obtained assuming range-dependent, stationary ocean and perfectly known source/receiver geometry.

TRANSITIONS

None yet.

RELATED PROJECTS

None.

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